Contribution of the electromagnetic pre-seismic emissions in the comprehension of the earthquake preparation process

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Abstract: Fracture induced electromagnetic (EM) fields allow a real-time monitoring of damage evolution in materials during mechanical loading in the laboratory. Pre-seismic electromagnetic emissions have been consistently detected prior to significant on-land or near coast-line earthquakes. This contribution presents a review of our work on the comprehension of the earthquake preparation process through the acquisition and analysis of electromagnetic pre-seismic emissions. Our work focuses on the answer of 3 crucial questions: (1) "How can we recognize an electromagnetic observation as a pre-seismic one?", (2) "How can we link an individual electromagnetic precursor with a distinctive stage of the earthquake preparation?", (3) "How can we identify precursory symptoms in electromagnetic observations which signify that the occurrence of the prepared earthquake is unavoidable?". The main result of our research is that fracture induced MHz-kHz EM physical fields allow real-time step-by-step monitoring of damage evolution of materials in the focal area during mechanical loading, as it happens at the laboratory scale. This result has been revealed though a multidisciplinary analysis.

1. The state of the art at the beginning of the investigation

A vital problem in material science is the identification of precursors of macroscopic defects or shocks. Fracture induced physical fields allow a real-time monitoring of damage evolution in materials during mechanical loading. A stressed rock behaves like a stress-EM transducer.

Improvements in *MHz-kHz electromagnetic (EM) emission* technique have permitted such a monitoring. MHz–kHz EM precursors are detectable not only at the laboratory but also at the geological scale.

Our basic idea was that fracture induced MHz-kHz EM fields should also permit the monitoring in real-time step-by-step of the gradual damage of stressed materi-

als in the Earth's crust, as it happens at the laboratory experiments.

In our opinion, an interesting experimental research would be the parallel monitoring of the corresponding observable manifestations of both laboratory and geophysical scale fracture phenomena. Based on this idea we have installed a field experimental network using the same instrumentation as in laboratory experiments for the recording of geophysical scale EM emissions. Consequently, our main observational tool is the monitoring of the fractures which occur in the focal area before the final break-up, decoding information hidden in the associated MHz-kHz EM time series.

Since 1994, a station has been installed and operated at a mountainous site of Zante island in the Ionian Sea (western Greece). The main aim of this station is the detection of kHz-MHz EM precursors. Six loop antennas detect the three components (EW, NS, and vertical) of the variations of the magnetic field at 3 kHz and 10 kHz respectively; three vertical $\lambda/2$ electric dipoles detect the electric field variations at 41, 54 MHz, and 135 MHz respectively. Moreover, two {\it Short Thin Wire Antennas}, oriented at EW and NS directions of length of 100 m, respectively, have been also installed. The aim of the last installation is the detection of a different type precursor, namely, ultra-low-frequency (<1 Hz) EM precursor rooted in a pre-seismic lithosphere-atmosphere-ionosphere-coupling.

Such an experimental setup helps to specify not only whether or not a single EM anomaly is preseismic in itself, but mainly whether a sequence of three EM disturbances at different frequencies emerging one after the other in a short time period and each of them satisfying an austere set of criteria, could be characterized as preseismic one.

Are there credible EQ precursors? This is a question of debate in the scientific community. Pre-seismic EM signals have not been adequately accepted as real physical precursory quantities. There may be legitimate reasons for the expressed critical views. The degree to which we can predict a phenomenon is often measured by how well we understand it. However, many questions about fracture processes of heterogeneous media remain standing. Especially, many aspects of EQ generation still escape our full understanding.

The ample understanding of fracture induced EM precursors *in terms of physics* is an open research target. In our opinion that is a path to achieve a more in-depth knowledge of the last stages of the fracture / EQ preparation process and thus more efficient short-term fracture / earthquake prediction in the future. A "seismic" shift in thinking towards basic science will result to a renaissance of a better understanding of EQ generation and strict definitions of EM precursors; no scientific prediction is possible without an exact definition of the anticipated phenomenon.

2. Our proposal for the study of MHz and kHz EM precursors

Based on the above mentioned concepts, we began to study the possible seis-

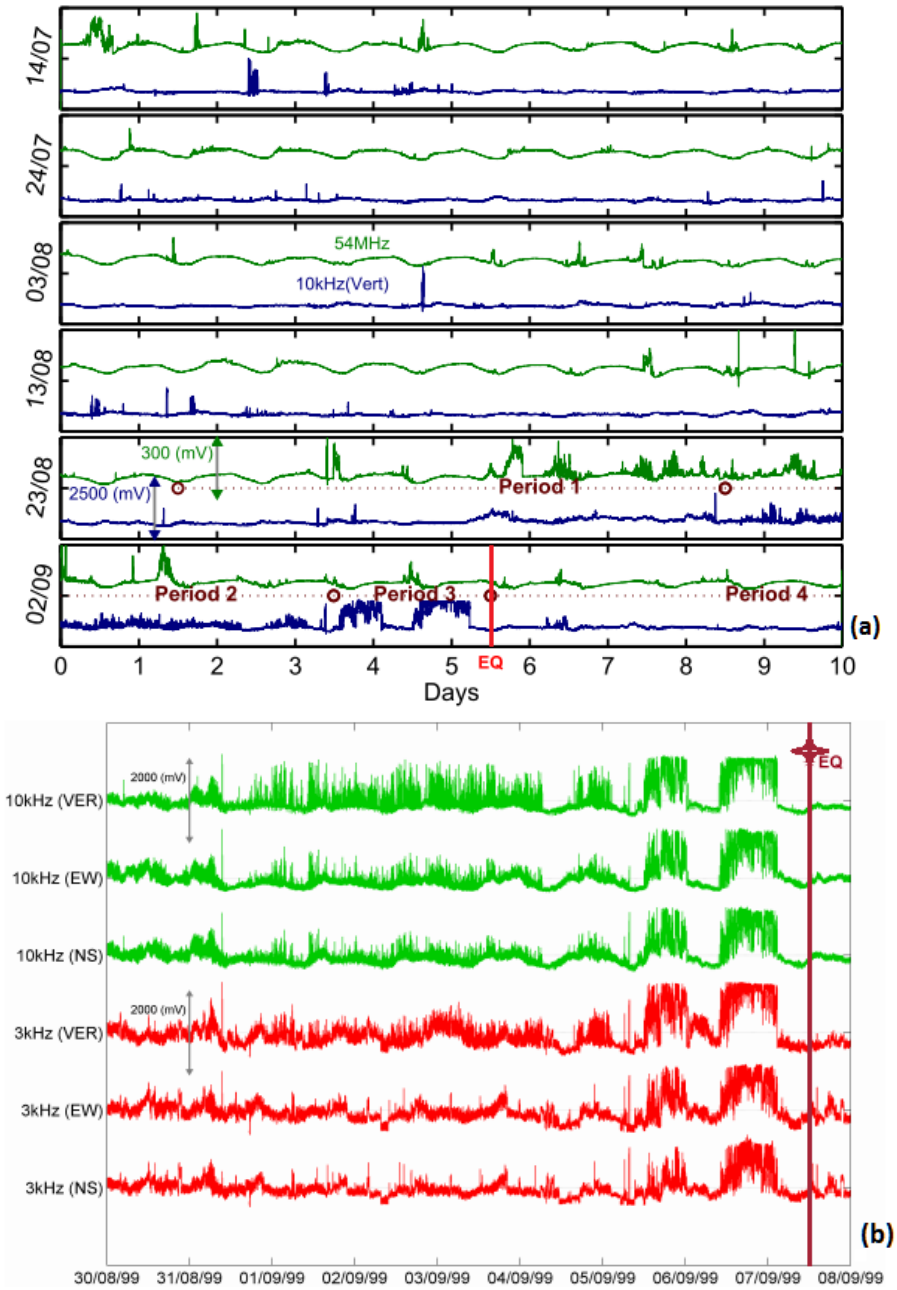

Figure 1. (a) Records from Zante station at 10 kHz (blue line) and 54 MHz (green line) for the time period from 14 July 1999 to 12 September 1999 (1 min averaged data). The red solid line denotes the exact time of the EQ occurrence. (b) EM emissions from Zante station at the 3 and 10 KHz loop antennas which preceded the Ms (ATH) = 5.9 Athens EQ on 7 September 1999 at 11:56:50 UT, from 30 August to 8 September 1999 (sampling rate 1sample/sec).

mogenic origin of the MHz-kHz anomalies recorded prior to significant surface EQs that occurred in land asking three fundamental questions:

- *How can we recognize an EM observation as a pre-seismic one?*
- *How can we link an individual EM precursor with a distinctive stage of the EQ preparation process?*
- *How can we identify precursory symptoms in EM observations that indicate that the occurrence of the EQ is unavoidable?*

The basic information that guided our thinking was the following well established evidence. An important feature, observed both at laboratory and geophysical scale, is that the MHz radiation precedes the kHz one (e.g. Fig. 1), indicating that they correspond to different characteristic stages of the fracture / EQ preparation process. We introduced the following two-stage model:

(i) The initially emerging MHz EM field originates from the cracking in the highly heterogeneous material that surrounds the backbone of asperities, distributed along the stressed fault sustaining the system;

(ii) The abrupt emergence of strong avalanche-like kHz EM is thought to be due to the fracture of the family of asperities themselves.

Our studies have shown that the MHz and kHz EM physical fields refer to completely different fracture mechanisms.

Main relevant publications: 6, 7, 8, 10, 15, 16, 25, 27, 28, 33, 34, 35, 36, 37, 38, 45, 46, 47, 48, 49, 50.

3. Focus on MHz EM field

We have shown that the dynamics of MHz EM physical field is characterized by antopersistency, namely, a negative feedback mechanism that "kicks" the crack-opening rate away from extremes. The heterogeneity leads to this behavior. Importantly, we have proven that this EM field is described in analogy with a thermal, continuous, second order transition in equilibrium.

The MHz EM anomaly includes the critical feature of **''symmetry breaking''** that permits **real-time step-by-step monitoring** of damage evolution of heterogeneous component in the focal area during mechanical loading (Fig. 2). Indeed, our analysis reveals the following consecutive epochs as the EQ approaches:

(i) The critical epoch (critical window) during which the short-range correlations between the opening cracks evolve to long-range ones.

(ii) The epoch of **the "symmetry breaking"** occurrence, namely, the transition from the phase of non-directional, almost symmetrical, cracking distribution to a directional localized cracking zone.

(iii) The integration of the "symmetry breaking". The rupture process has been obstructed at the boundary of the backbone of strong asperities.

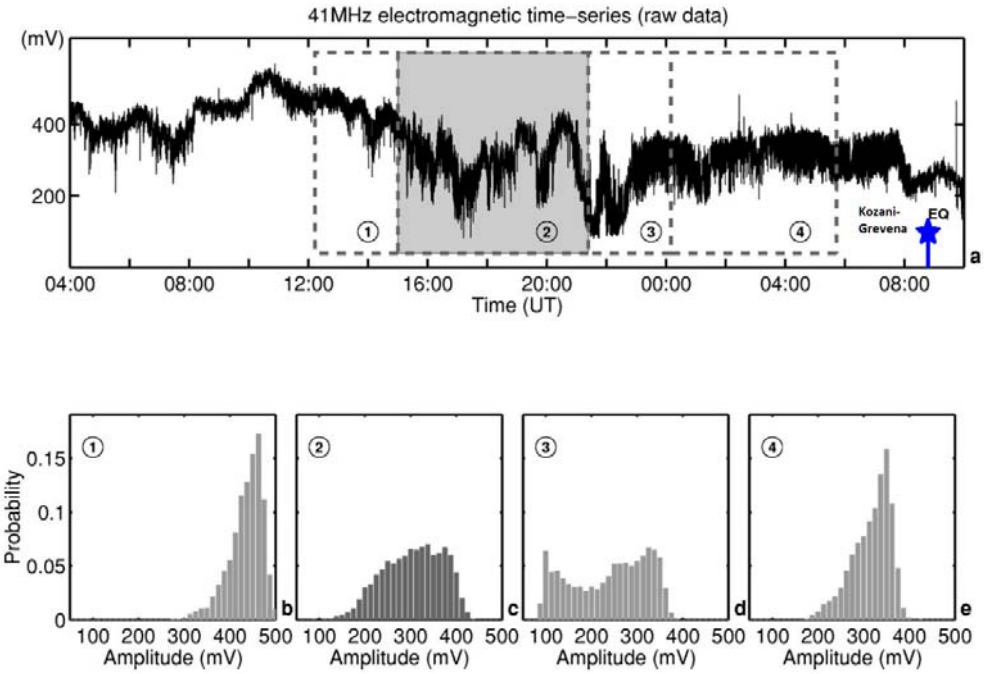

Figure 2. (a) The 41-MHz time series associated with the Kozani-Grevena earthquake. The blue star indicates the time of the earthquake occurrence. (b) – (e) show the distribution of the amplitude of electromagnetic pulses for four consecutive time intervals marked in (a). The second (shaded) time interval determines, in terms of the method of critical fluctuations (MCF), the crucial time interval during which the short-range correlations evolve to long range (critical window); the corresponding distribution (c) might be considered to be a precursor of the impending symmetry breaking readily observable in the subsequent time interval (d). The distribution in s e d is very similar to that of (b), while here there is an upward shift of the values to the range of the second lobe of the distribution in (d); the appearance of the distribution in the (e) may indicate that the symmetry breaking in the underlying fractoelectromagnetic mechanism has been almost completed. The aforementioned evolution is expected in the framework of the hypothesis that the fracture in the highly disordered media develops as a kind of generalized continuous phase transition.

A crucial question refers to what is the physical mechanism that organizes the heterogeneous system in its critical state? Combining ideas of: Levy statistics, nonextensive Tsallis statistical mechanics, and criticality with features hidden in the precursory MHz time-series we showed that a truncated Levy walk type mechanism can organize the heterogeneous system to criticality. The study of a numerically produced truncated Levy walk supported and extended our results. We note that, unlike the MHz EM anomalies, the kHz EM anomalies could not be described in analogy with a continuous thermal phase transition or by a truncated Levy mechanism.

A major problem in this field of research is to restrict the study to the MHz EM anomalies which are associated with the preparation of fracture phenomena *solely*, filtering out from the data possible disturbances due to other sources, e.g. solar flare activity. Based on the aforementioned refined definition of fracture induced MHz EM anomaly we proposed criteria for such a successful discrimination which are in contraction with those reported previously.

We have proposed, in contradiction to the up till then prevailing views, that the appearance of a MHz EM anomaly due to its nature is a necessary but not sufficient requirement for the EQ We suggested that the occurrence. The integration of ''symmetry breaking'' simply means that the "siege" of asperities has already been started**. The abrupt emergence of strong avalanche-like kHz EM activity** reveals the fracture of asperities, if and when the local stress exceeds their fracture stress**.**

Main relevant publications: 6, 7, 8, 10, 15, 16, 28, 33, 35, 36, 37, 50.

4. Focus on kHz EM field

The notably crucial character of the former suggestion, (it implies that the occurrence of the ensuing EQ is unavoidable) requires a strong support by well established arguments. Based on physically powerful arguments we have satisfied this obligation.

First, based on a multidisciplinary statistical analysis we have shown that the kHz EM time series are characterized by the following crucial symptoms of an extreme phenomenon:

(i) High organization or high information content. Tools of information theory, concepts of entropy rooted in the extensive and nonextensive Tsallis statistical mechanics, and measures of complexity have been used in order to identify the aforementioned features (Shannon n-block entropy, Shannon n-block entropy per letter, conditional entropy, entropy of the source, Kolmogorov-Sinai entropy, T-entropy, Approximate Entropy (ApEn), Fisher Information, Correlation Dimension, R/S analysis, Detrended Fluctuation Analysis, Fractal Dimension, and finally fractal wavelet spectral analysis) (e.g., Fig. 3).

(ii) Strong persistency, indicating the presence of a positive feedback mechanism in the underlying fracto-EM mechanism that leads the systems out of equilibrium.

(iii) Existence of clear preferred direction of fracture activities.

(iv) Absence of any footprint of a second order transition in equilibrium or truncated-Levy- walk type mechanism.

The aforementioned results not only clearly discriminate the recorded kHz anomalies from the background noise, but are consistent with the endorsement of the kHz EM anomaly as image of an underlying extreme event.

In contradiction to the up till then prevailing views, from our point of view even the aforementioned multidisciplinary analysis per se does not link the kHz EM phenomenon with the fracture of asperities. The aforementioned statistical results are likely to offer necessary but not sufficient criteria in order to recognize a kHz EM anomaly as indicator of the fracture of asperities. The crucial question was whether different approaches could provide additional information that would allow one to accept that the kHz EM anomalies signalize the fracture of asperities.

Main relevant publications: 17, 23, 24, 26, 35, 36, 45, 47, 46, 50.

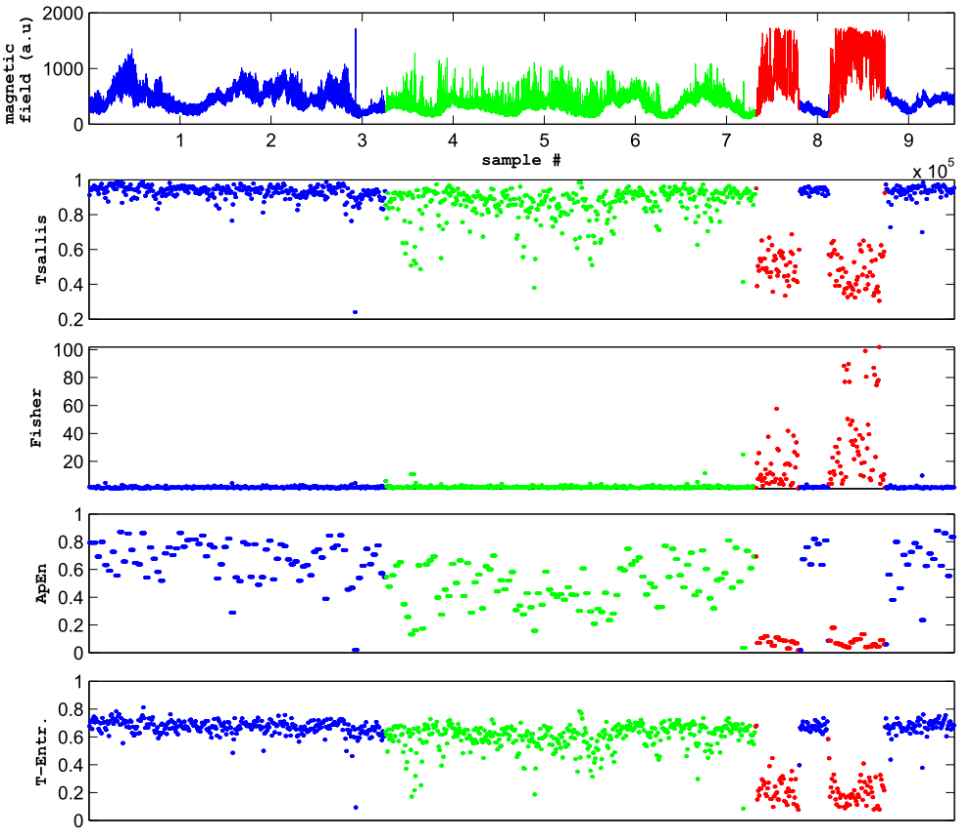

Figure 3. The upper part depicts the EM time series associated with the Athens earthquake recorded by the 10 kHz magnetic sensor. The blue part refers to the background noise. The green and red parts refer to the two distinct epochs of the emerged preseismic EM activity (see text). The next sub-figures show the temporal evolution of Tsallis entropy, Fisher information, Approximate entropy and T-entropy, respectively, using fixed windows of 1024 samples each.

Our proposal:

The basic information that guided our thinking was the following well established evidence: Despite the complexity of fracture process, there are universally holding

scaling relations. The aspect of **self-affine** nature of faulting and fracture is widely documented. From our point of view, universal structural patterns of fracture process should be included into a precursor associated with the fracture of asperities.

We have shown that our suggestion is satisfied. We have proved that the activation of a single fault by means of the associated kHz EM radiation behaves as a reduced image of the regional seismicity covering many faults and a reduced image of laboratory seismicity in terms of acoustic or EM emission, correspondingly. In the following, we present the hitherto published relevant arguments by our group. All these arguments have appeared for the first time in the literature.

A. Argument in terms of *Gutenberg-Richter law*

We have found that both the amplitudes and energies of the "EM events" included in a detected kHz EM precursor follow the *Gutenberg-Richter law* with exponents consistent with other critical realizations (Acoustic Emissions, Electromagnetic Emissions) obtained there via real laboratory measurements, theoretical predictions or computer simulations even with EQs.

Main relevant publications: 11, 20, 27, 36, 50.

B. Arguments in terms of non-extensive statistical mechanics

A recently introduced model for EQ dynamics based on a nonextensive Tsallis statistical mechanics, starting from first principles, i.e., a nonextensive formulation of the maximum entropy principle, leads to a G-R type law for the magnitude distribution of EQs. The proposed nonextensive G-R type law provides an excellent fit to seismicities generated in various large geographic areas covering many geological faults. We have shown that the nonextensive formula efficiently describes the distribution of magnitudes of the detected fracto-EM events (''Electromagnetic Earthquakes''), as well, with similar nonextensive q-parameter which measure the order of nonextensivity of the system (Fig. 4). This result implies that, the statistics of regional seismicity is merely a macroscopic reflection of the physical processes in a single earthquake source.

Main relevant publications: 27, 34, 36, 46, 49, 50.

C. Arguments by means of the aspect of universal fractional Brownian motion spatial profile in natural rock surfaces

Ample experimental and theoretical evidence strongly support the suggestion that natural rock surfaces can be represented by a spatial persistent fractional Brownian motion (fBm) scheme over a wide range, from the laboratory up to the geological scale. A fracto-EM precursor rooted in the relative displacement of fault faces should follow this scheme; a single EM burst occurs when there is an intersection between the two profiles of the fault. We have shown that the observed kHz EM time series really follows the persistent fBm model.

Main relevant publications: 14, 16, 29, 35, 36, 46, 50.

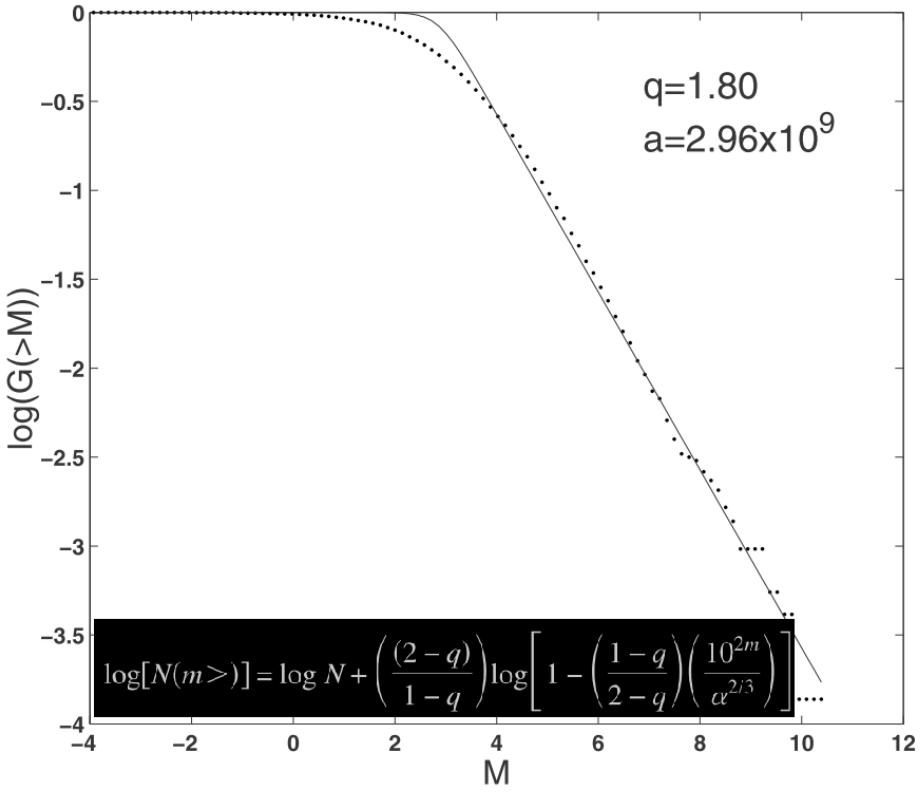

Figure 4. We use the embedded nonextensive formula to calculate the relative cumulative number of electromagnetic earthquakes G(>M), included in the whole precursory phenomenon, namely, in the phases "Period 2" and "Period 3" depicted in Fig. 1. There is an agreement of the formula with the data. The associated parameters are $q = 1.80$ and $a = 2.96 \times 10^{-9}$.

D. Arguments by means of the aspect of universal spatial roughness of fracture surfaces

The surface roughness has also been interpreted as a universal indicator of surface fracture, weakly dependent on the nature of the material and on the failure mode. This universal indicator of surface roughness should characterize the roughness of the profile of a seismogenic kHz EM time series. We have shown that it really happens.

Main relevant publications: 29, 36, 38, 50.

E. Arguments by means of fault modeling

An observed kHz EM emission, which is truly related with the fracture of asperities, should be consistent with the fault modeling of the occurred EQ which has been resulted by studies from different disciplines. We have shown that such a cru-

cial relation exists in terms of energy, information content (Fisher information) and organization (Approximate Entropy). More precisely, two kHz EM anomalies have been detected before the Athens EQ. The larger anomaly, the second one that has been recorded, contains approximately 80% of the total EM energy release. The fault modeling based on information obtained by satellite radar interferometry predicts two faults. The main fault segment is responsible for 80% of the total seismic energy released, while the secondary fault segment for the remaining 20%. A seismic analysis leaded to similar results. The aforementioned compatibility in terms of energy is further extended by means of information content, and order of organization, as well (Fig. 5).

Main relevant publications: 2, 47.

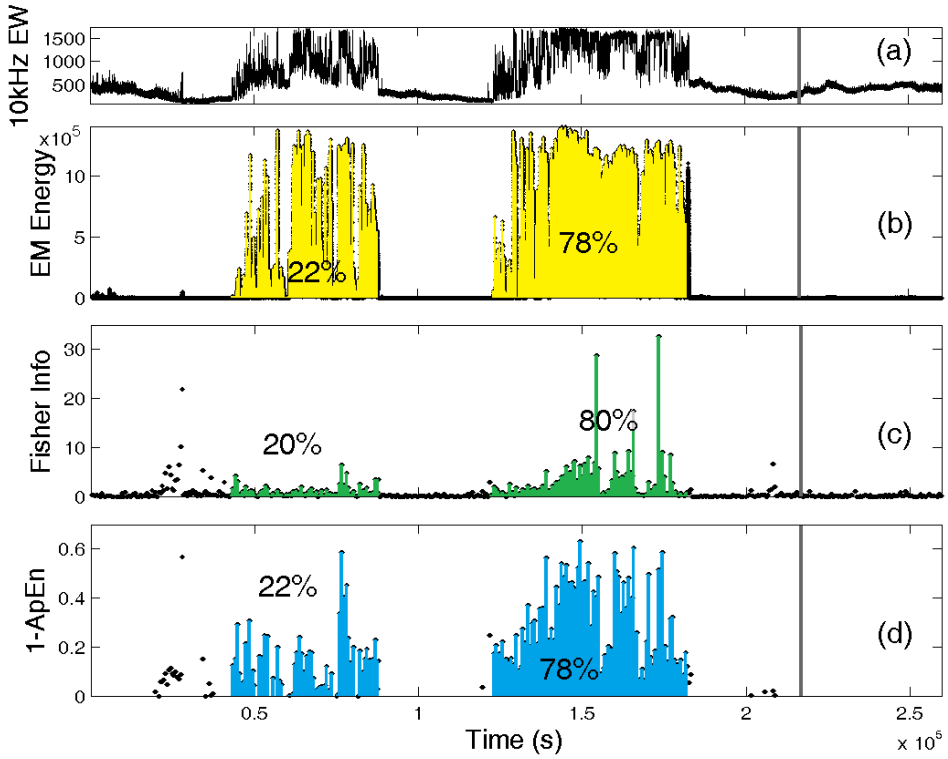

Figure 5. (a) The two strong impulsive bursts in the tail of the recorded pre-seismic kHz EM emission (10kHz, East-West, magnetic field strength in arbitrary units) prior to Athens EQ (please refer to Fig. 1). For the specific signal excerpt, the EM Energy (in arbitrary units) (b), the Fisher information (c) and approximate entropy (d) evolution with time are presented. The grey areas indicate the energy, information and 1-ApEn corresponding to the two bursts. The first (left) burst is responsible for the 22% of the EM energy, the 20% of the Fisher information, and the 22% of the ApEn, while the second (right) for the 78%, 80%, and 78% respectively. All graphs are time aligned for direct reference. The time of the EQ occurrence is indicated by the thick vertical grey line.

F. Arguments by means of fractal-electrodynamics - The notion of fractal radiating geo-antenna

An EQ occurs on the fractal structure of a fault: a network of line fractured elements having a fractal distribution in space is formed as the EQ approaches. The emitting, diffusing and recombination charge accompanying the micro-fracturing, can act as a current generation during crack opening. In this view, an active crack, or rupture, can be simulated as a "radiating element." We have proposed that as the shock is approaching a fractal radiating geo-antenna (FRGA) is forming which should explain the observed fractal phenomenology in precursory EM emissions. We have verified this prediction in terms of fractal electrodynamics that combines fractal geometry with Maxwell's equations of electrodynamics. We note that the fractal dimension of the FRGA is consistent with that of faults as it has been estimated from laboratory and geological data. Such an antenna radiates more efficiently compared to a single dipole antenna: fractals are highly convoluted, irregular shapes and sharp edges, corners and discontinuities enhance radiation from electric systems. The existence of a FRGA enhances the possibility of detection of precursory EM emissions.

Relevant publication: 9.

G. Study by means of laboratory experiments in the frame of meso-mechanics

In the recent years a new approach to the description of plastic deformation and failure of solids based on synergetic principles of physical meso-mechanics is intensively developing. The basic idea is that a solid under deformation is considered as a multilevel self-organized system. The plastic flow of a loaded material is pertained to its stability loss at micro-, meso-, and macro-scale levels. We showed that the scale levels of plastic deformation localization of an ionic crystal under compression are qualitatively similar to those under tension of metal material. We also showed that the consecutively emerging MHz and kHz EM modes at large scale may signalize the transition of plastic flow localization from the meso-scale to the macro-scale, culminating in global fracture. More precisely, based on data from compression testing of ion crystals and rocks, polycrystals under cycling loading, as well as the results of computer simulation of crack formation in brittle materials, we developed the hypothesis that the MHz mode is connected with the formation of small meso-scale fragments while the kHz mode is related to the formation of large meso-blocks during the loading and relative displacement of fault faces. A qualitative scheme of multiple cracking in terms of meso-mechanics at the last stages of EQ preparation process has been proposed, which is consistent with a satellite image of the fragmentation produced by a large EQ of magnitude Mw = 7.8 .

Main relevant publications: 3, 13, 25.

H. Study by means of laboratory acoustic and EM emissions.

Any reported in the literature laboratory kHz pre-fracture feature of these two emissions are included in the observed pre-seismic kHz EM phenomena at the field. We pay attention to the fact that laboratory results show that strong kHz EM signals are generated only during sharp drops in stress. This evidence strongly links the kHz EM signals with the fracture of asperities.

Main relevant publications: 4, 12, 13, 17, 20, 24.

5. On the puzzling features

Puzzling features'' are systematically observed in seismogenic MHz-kHz EM emissions. EM quiescence is appeared in all frequency bands during the aftershock period. Experiments on rocks have revealed evidence for non-linearity, hysteresis and discrete memory in their elastic behavior. EME, as a phenomenon rooted in damage process, should be an indicator of memory effects, as well. We have proposed that this quiescence mirrors the memory effects that take place in rocks subjected to cycling loading, especially Kaiser Effect: during cyclic loading, the level of EM emissions increases significantly when the stress exceeds the maximum previously reached stress level. The stress during the aftershocks period does not exceed the maximum previously reached stress level associated with the main shock occurrence.

EM quiescence is also appeared in all frequency bands just before the main shock occurrence. The systematically observed MHz EM pre-seismic quiescence is fully understood in the frame of the proposed two-stage model. This emission stops when the fracture of the heterogeneous material has been completed and the stresses siege the family of strong asperities; the prepared EQ will occur if and when the local stress exceeds fracture stresses of strong entities.

Concerning the kHz EM quiescence, numerous recent laboratory tests reveal that EM signals are generated only during sharp drops in stress that are attributed to a rapid decay of the mechanical properties. This result is in consistency with our suggestion that the natural kHz EM fields signalize the fracture of asperities. Moreover, laboratory studies have revealed a significant decrease of elastic moduli just before the global failure occurrence. The sudden drop in the amount of the kHz EM energy release could be due to the abrupt decrease of the elastic moduli. On the other hand, laboratory experiments indicate that the efficiency of generating EM emission is higher in tensile cracks than in shear cracks. In this picture it is reasonable to expect EM quiescence just before the main shock, because the latter is considered to be a result of shear faulting, which may not be very efficient for creation of a fresh surface. In any case the kHz EM quiescence remains as a puzzling feature.

Main relevant publications: 1, 11, 20.

6. Transferring ideas from laboratory to geophysical scale

An important open question in the large scale is whether transient stresses from a large EQ can be responsible for the triggering of another significant remote EQ. The consequent question is whether we can identify precursory features that signalize the triggering of a new significant event in a new rather remote region. Laboratory experiments have justified such a triggering; they have shown that, during a fracture, the breaking of a bond launches a propagating stress wave which triggers the breaking of other bonds. We examined whether the same holds at the geophysical scale. We showed that the answer is positive by simultaneous analyses of seismicity and kHz EM activity in terms of nonextensive statistical mechanics, Hurst exponent, and Fisher Information. We have shown that the launch of the first large EQ leads to the appearance of significantly higher nonextensivity, persistency, and information content in the seismicity around the new epicenter. Moreover, we found that the statistics of this foreshock seismicity is merely a macroscopic reflection of the physical processes in the new EQ source as it is mirrored in the associated kHz EM activity. Notice that these results could indicate the possible position of the epicenter of the impending EQ.

Relevant publication: 49

6.1 On the discrimination of the model that follows the activated fault

We have further examined and elucidated the link of the precursory kHz EM activity with the last stage of EQ generation building on two theoretical models for EQ dynamics (Fig. 6). The first self-affine asperity model states that the EQ is due to the slipping of two rough and rigid Brownian profiles one over the other. In this scheme, an individual EQ occurs when there is an intersection between the two fractional Brownian profiles. The second model, which is rooted in a nonextensive Tsallis framework starting from first principles, consists of two rough profiles interacting via fragments filling the gap. In this nonextensive approach, the mechanism of triggering EQ is established through the interaction of the irregularities of

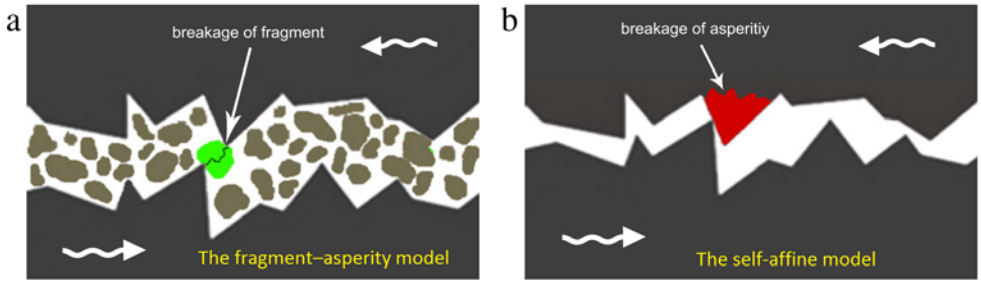

Figure 6. (a) An illustration of the fragment–asperity model. EM fluctuations are emitted during the fracture of fragments. (b) An illustration of the self-affine model. EM fluctuations are emitted during the fracture of strong and large ‘‘teeth’’.

the fault planes and the fragments between them. We showed that two models of EQ dynamics complement each other, in a sense, and both are mirrored in the detected preseismic kHz EM emissions. We presented arguments by means of nonextensive statistical machanics, T-entropy, and Hurst exponent that permit to discriminate via the associated kHz EM anomaly whether the activation of a fault follows the self-affine asperity model or nonextensive fragment model.

Relevant publication: 46

7. The science of EQ preparation should, from the start, be multi-disciplinary

EQ's preparatory process has various facets which may be observed before the final catastrophe. A candidate preseismic kHz-MHz EM activity should be consistent with other EM precursors precursors rooted in lithosphere or lithosphere-atmosphere-ionosphere coupling and precursors which are imposed by data from

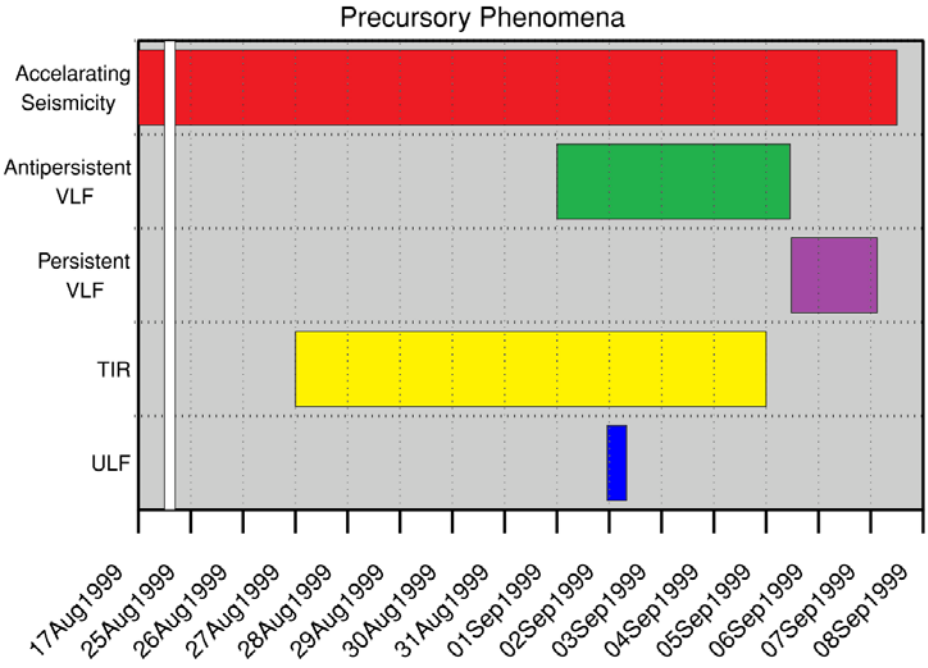

Figure 7. Prior to the Athens earthquake, the following candidate precursors have been reported: (i) an accelerating seismic energy release in the area around the epicenter of the Athens event, (ii) an accelerating Very Low Frequency electromagnetic emission. The first part of this activity shows antipersistent behavior, while, the tail of this EM precursor exhibits persistent character (iii) a sequence of TIR signals that exhibits a progressive increase of its intensity in the area around the pre-focal zone, and finally (iv) a SES activity (Ultra Low Frequency—geoelectric potential differences). Note that fault modeling based on information obtained by satellite radar interferometry predicted two faults (see also Fig. 5).

other disciplines such as: Seismology, Infrared Remote Sensing, Synthetic Aperture Radars Interferometry, e.t.c. The sequential appearance of different precursors in a relative short time interval supports the seismogenic origin of each of them, increases the probability that a significant EQ is coming, and leads to higher estimation accuracy of its parameters, namely, magnitude, time and position. This requirement has been satisfied (Fig. 7).

Main relevant publications: 1, 11, 17, 20, 24.

8. Study by means of complex systems

A corollary in the study of complex systems is that by transferring well documented ideas and results from investigations in hitherto disparate areas we can check our proposals and results. We have compared the results and ideas resulted by the studies of MHz-kHz EM fields with corresponding ones resulted by the studies of epileptic seizures, magnetic storms, and solar flares. This comparison is justified. Despite having different causes, the aforementioned complex systems are similar to kHz EM phenomenon in many respects, for example, they are characterized by highly intricate tangle, cluster and hierarchical structures, spatio-temporal correlation with feedback, self-organization, connection diversity, and impulsive localized release of energy. The relevant study gave us the possibility to:

Cross-fertilize our statistical proposals in the study of kHz EM field.

Our multidisciplinary statistical analyses of the aforementioned three extreme events in terms of extensive and non extensive statistical mechanics have revealed the existence of common statistical pathological symptoms *(clear preferred direction of elementary activities, strong persistency, and high organization*) They are interpreted as a crucial increase in the susceptibility of the system in the supercritical state, where any small instability can provoke large-scale reactions accompanied by essential energy release. Importantly the aforementioned common crucial pathological patterns are in surprising agreement with those included in the kHz EM field under study.

Our studies have revealed the existence of two different regimes in the dynamics of magnetosphere. The sub-storm dynamics is characterized by antipersistency and resembles second-order phase transition, while, magnetic storms show persistency and include the features of a first-order *non-equilibrium* transition. This scheme of two different regimes in the dynamics of magnetosphere is in striking similarity with the proposed two stage model of EQ dynamics in terms of pre-seismic MHz-kHz EM anomalies. The epileptic seizure also follows the aforementioned scheme of two different regimes, as well. Consequently, the introduced two stage model of EQ dynamics seems to have a universal character in the study of extreme events, as well.

Our results have shown that the crust of the earth is not in a state of continuous Self-Organized- Criticality that implies a system perpetually near instability, hence

reducing the predictability of individual events. On the contrary, our results suggest that the crust follows the scheme of the ''Intermittent Criticality'' which permits a degree of predictability. Our finding showed that the magnetosphere also follows the Intermittent Criticality.

Based on our analyses, we have shown that, while the magnetosphere is mostly driven by the solar wind, the critical state of magnetosphere is the result of a combination of solar wind and internal magnetospheric rather than solar wind variations alone. This exactly happens in the case of EQ generation process.

The evidence of a common statistical behavior in the studied diverse systems raises deep questions concerning the existence of a common basic mechanism.

Examine the existence of common scaling laws in different complex phenomena. Extreme phenomena are characterized by great complexity, however, some simple laws that exhibit scale invariance governs the statistics of their occurrence. The traditional Gutenberg-Richter law which describes the magnitude distribution of EQs is a characteristic example. The origin of these scaling behaviors is not yet fully understood and a natural fundamental question concerns the existence of common scaling laws in different complex phenomena. We found that the distribution of magnitudes of solar flares, magnetic storms, electrical pulses included in a single epileptic seizure, EQs occurred in various seismic regions each of them covering many faults, and "electromagnetic earthquakes" included in an observed kHz EM phenomenon associated with the activation of a single fault are nicely described not only by the Gutenberg-Richter law (*with similar b-value*), but also a nonextensive formula, which has been derived in terms of a nonextensive model for EQ dynamics, with similar q-parameter that reflects the order of the nonextensivity of the system..

The aforementioned results show that the seismogenic kHz EM field, magnetic storms, epileptic seizures and solar flares have certain quantitative features that are intriguingly similar. These properties can be conveniently grouped under the headings of: (i) **Scale invariance,** which signalizes a hierarchical organization that results in power law behavior of some control parameter, while the exponent of power law is a number characterizing the system. (ii) **Universality**, which means that all the exponents found for the studied diverse systems are similar. The evidence of these two features strongly enhances the seismogenic origin of the observed kHz EM emissions, and helps in a better understanding and in developing generalized views of above mentioned different phenomena.

Lead to important new results. Self-similar complex systems are characterized by continuous scale invariance and, in response, the existence of power laws. However, many complex systems exhibit *discrete scale invariance* (DSI), a weaker form of scale invariance symmetry, which in turn leads to log-periodic corrections to scaling that decorate the pure power law. We have presented results of a search of log-periodic corrections to scaling in the squares of Dst index increments which are taken as proxies of the energy dissipation rate in the magnetosphere. We have

shown for the first time that the dynamics of magnetosphere exhibits DSI. This indicates that the underlying physical mechanism has characteristic length scales. This is extremely interesting as this provides important constraints on the underlying physics. We also have discussed the possible implications of the existence of DSI on space weather forecasting efforts. For prediction purposes, it is much more constrained and thus reliable to fit a part of oscillating data than a simple power law which can be quite degenerate especially in the presence of noise. This remark has been used and is vigorously investigated in several applied domains, such as EQs, rupture prediction, and financial crises.

Main relevant publications: 14, 18, 19, 30-32, 39-44.

9. Conclusion

Our research focuses on the last preparatory stage of earthquake generation using only ideas and tools of physics. Our view is that an earthquake is essentially a large scale fracture. We have installed a field experimental network using the same instrumentation as in laboratory experiments for the recording of geophysical scale EM emissions. In our opinion, a "seismic" shift in thinking towards basic science will result to a renaissance of a better understanding of EQ generation and strict definitions of EM precursors; no scientific prediction is possible without an exact definition of the anticipated phenomenon. We consider that this research has contributed to shedding light on the final stages of the earthquake preparation process. To the extent that this is right, it has also contributed to the earthquake prediction since this depends on the degree of comprehension of the involved processes.

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